Sixth Annual Conference on Carbon Capture & Sequestration

Expediting Deployment of Industrial Scale Systems

Coal to Liquids and Sequestration

Synthetic Gasoline and Diesel from Coal and Mixed Prairie Grasses for a Carbon-Constrained World

Robert H. Williams,[a] Stefano Consonni,[b]

Giulia Fiorese,[b] and Eric D. Larson[a]

[a]Princeton Environmental Institute, Princeton University

[b]Politecnico di Milano, Milan Italy

May 7-10, 2007 • Sheraton ad Station Square • Pittsburgh, Pennsylvania

WHY SYNFUELS FROM COAL/BIOMASS WITH CCS

- Transportation fuels challenges under BAU:
  - Climate change (*~ 1/3 of US fossil fuel CO_2 emissions…need to decarbonize*)
  - Oil supply insecurity (*~ 2/3 of US oil is imported*)
- Can *both* transportation fuel challenges be met:
  - With near-term technologies?
  - Without major infrastructure changes?
  - Without running up against land-use constraints?
  - Without major biodiversity loss?
  - Cost-effectively?

DILEMMA FOR CONVENTIONAL BIOFUELS

- Advantages:
  - Carbon neutrality
  - Renewability
- Downside:
  - Scarcity of high-quality land (*competition with food production*)
  - Biodiversity loss concerns about monoculture crops for energy
- Challenges can be addressed via
  - exploiting “negative emissions” potential of biomass
  - biomass/coal coprocessing for energy

TWO PART C-STORAGE STRATEGY FOR MAKING BIOMASS "C-NEGATIVE"

- *First part*,
  - Convert biomass via gasification
  - Separate out/store underground (*in geological formations*) as CO_2 most C in biomass not needed in final energy product

    ➔ negative CO_2 emissions
  - Coprocess biomass with coal (*also gasified*) to make synfuels and/or electricity—to exploit scale economies of coal conversion, low coal prices
- *Second part*,
  - Grow biomass as *mixed grasses on C-depleted soils*

    ➔ more negative CO_2 emissions via soil C/root C buildup
- Second part of strategy also addresses effectively biodiversity challenge posed by conventional biofuels

MAJOR FINDINGS OF TILMAN GROUP'S RESEARCH ON MIXED PRAIRIE GRASSES GROWN ON CARBON-DEPLETED SOILS

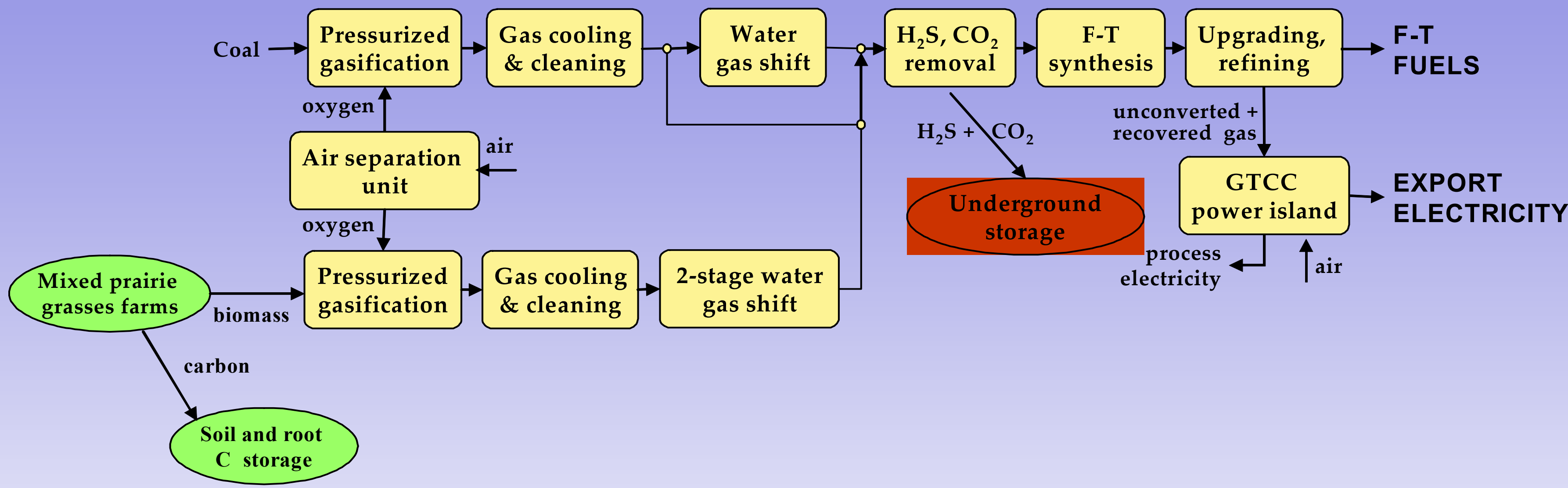
- Sustainable grass yield increases monotonically with # of species
- Soil/root C build-up increases monotonically with # of species
- Soil C build-up continues for ~ century or more
- Over 30 y, soil/root C buildup rate can average ~ 0.6 tC per tC in harvested biomass…with 16 species
- Once mixed prairie grasses (*MPGs*) have been established, only modest additional inputs are needed with annual harvesting (*e.g., gasifier ash*)
- High (energy output)/(energy input) ratio
- Local biodiversity gain vs. net biodiversity loss for monocultures

<u>Source</u>: D. Tilman et al., *Science,* **314**: 1598-1600, 8 December 2006

SCOPE OF ANALYSIS

- F-T liquids production via solids gasification:
  - Once-through liquid-phase reactor for F-T synthesis
  - Unconverted syngas used to make coproduct electricity in combined cycle
- Alternative polygeneration plants sited in S. Illinois:
  - Coal-fueled plant w/CO_2 vented (*GE entrained-flow quench gasifier*)
  - Coal-fueled plant w/CCS
  - Coal/MPG-fueled plant w/CCS (*GE gasifier for coal; GTI fluidized bed gasifier for biomass*)
- Minemouth plants using:
  - High S bituminous coal
  - MPGs grown on lands now growing corn
- E & C balances estimated—assigning to electricity the GHG emission rate of coal IGCC w/CCS and seeking 0 net GHG emission rate for FTL
- For assumed (*i*) \$100/tC GHG emissions value & (*ii*) electricity credit = generation cost for coal IGCC w/CCS, economic analysis carried out from perspectives of:
  - Synfuels producer
  - Farmers growing MPGs

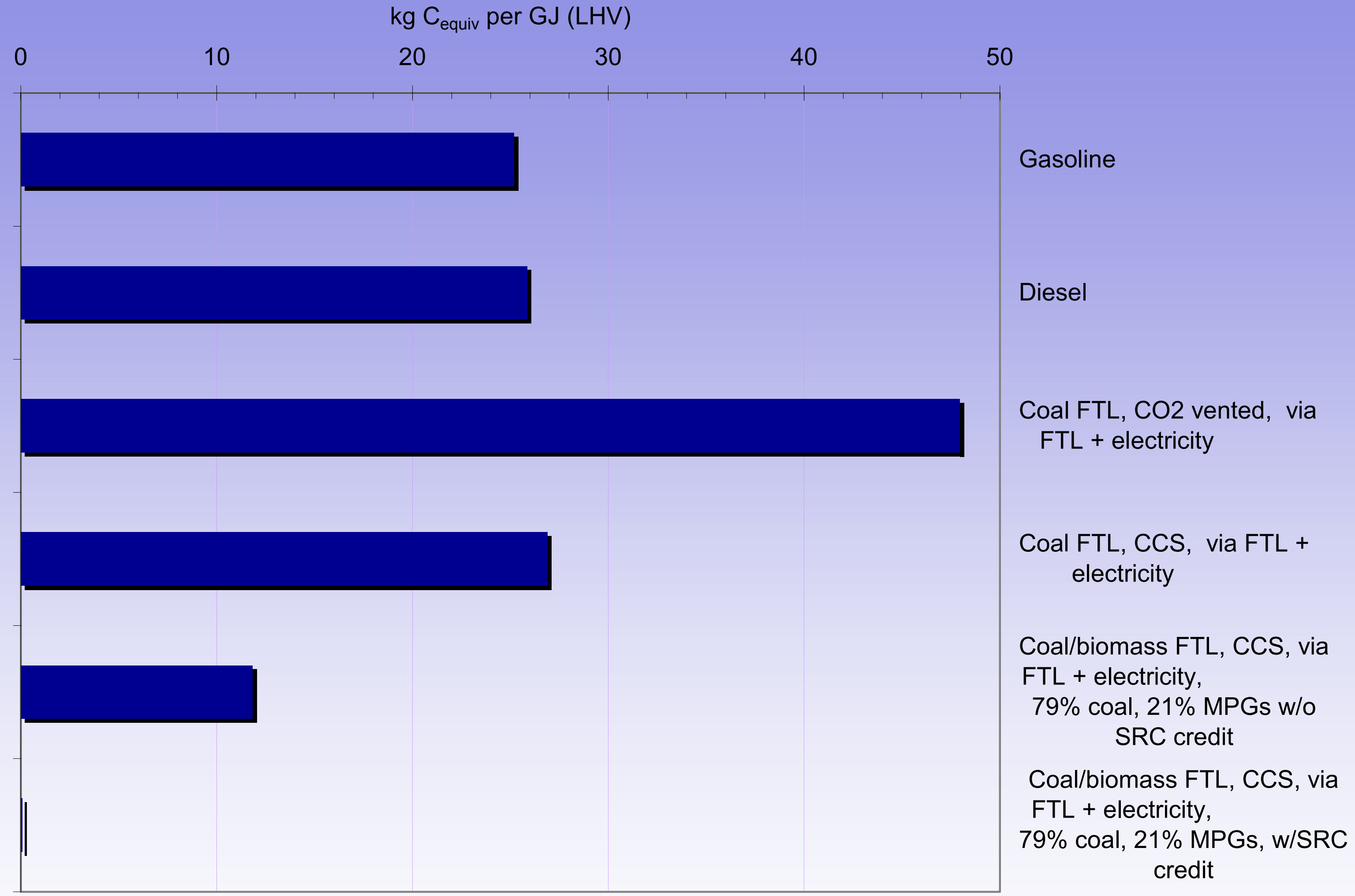
F-T FUELS + ELECTRICITY FROM COAL + MPGS WITH TWO C-STORAGE MECHANISMS



- Coprocessing benefits provided by coal:
  - --Scale economies of coal conversion
  - --Low cost of coal feedstock

- Biomass provides:
  - --negative GHG emissions benefit via photosynthetic CO_2 storage along with storage of CO_2 from coal
  - --Additional negative GHG emissions benefit from growing MPGs on C-depleted soils—up to 0.6 tC per tC in harvested biomass with 16 grasses

GHG Emission Rates for Fuel Production and Use



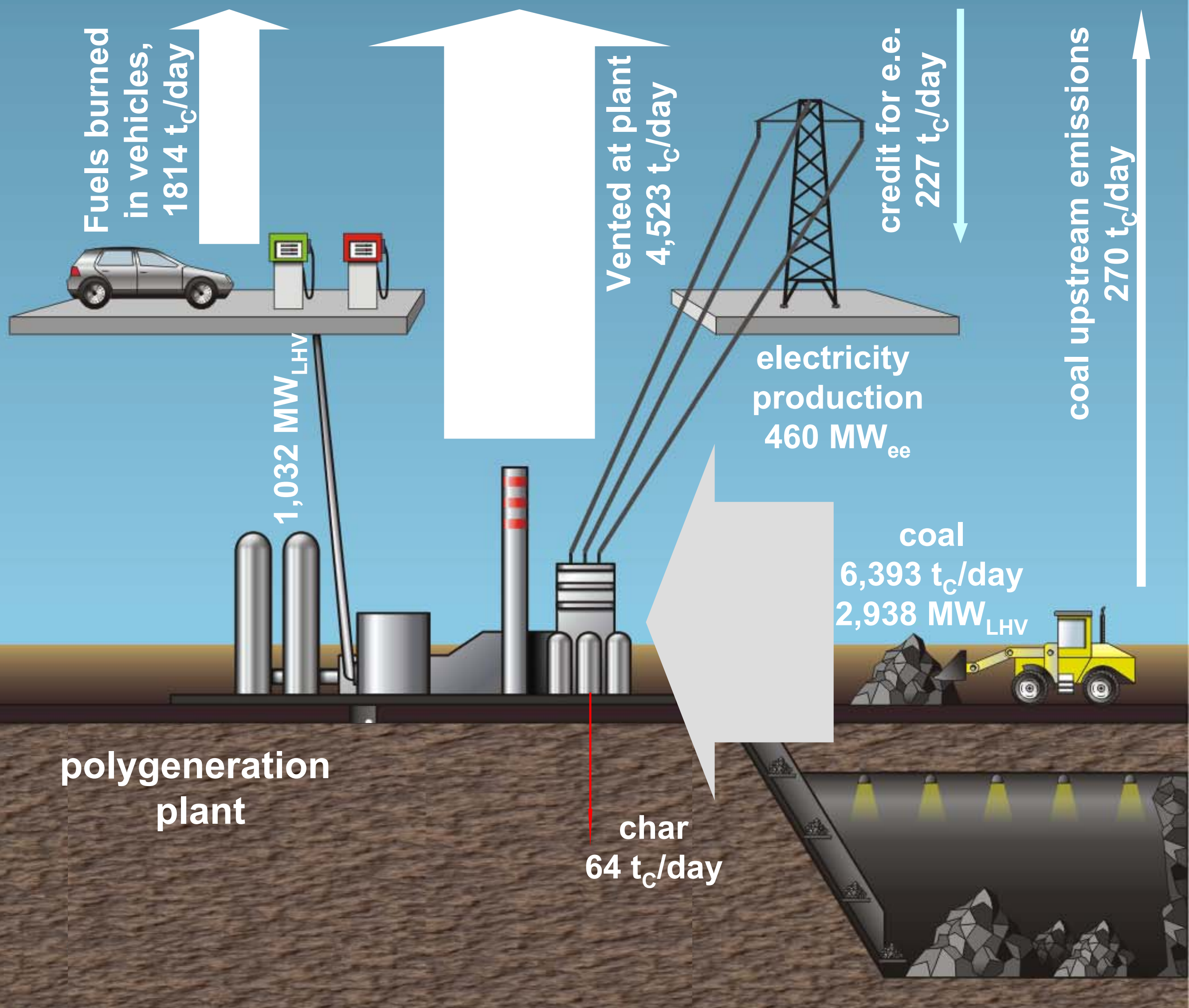
Amount of MPGs used = minimum for 0 FTL GHG emission rate when soil/root C storage rate = 0.6 tC per tC in harvested MPGs

COAL TO F-T LIQUIDS + ELECTRICITY, VENTED

C_{equiv} balances to atmosphere for F-T liquids

OUT: electricity credit (227 t_C/day)

IN: upstream emissions, vented at plant, fuels burned in vehicles (6,606 t_C/day)



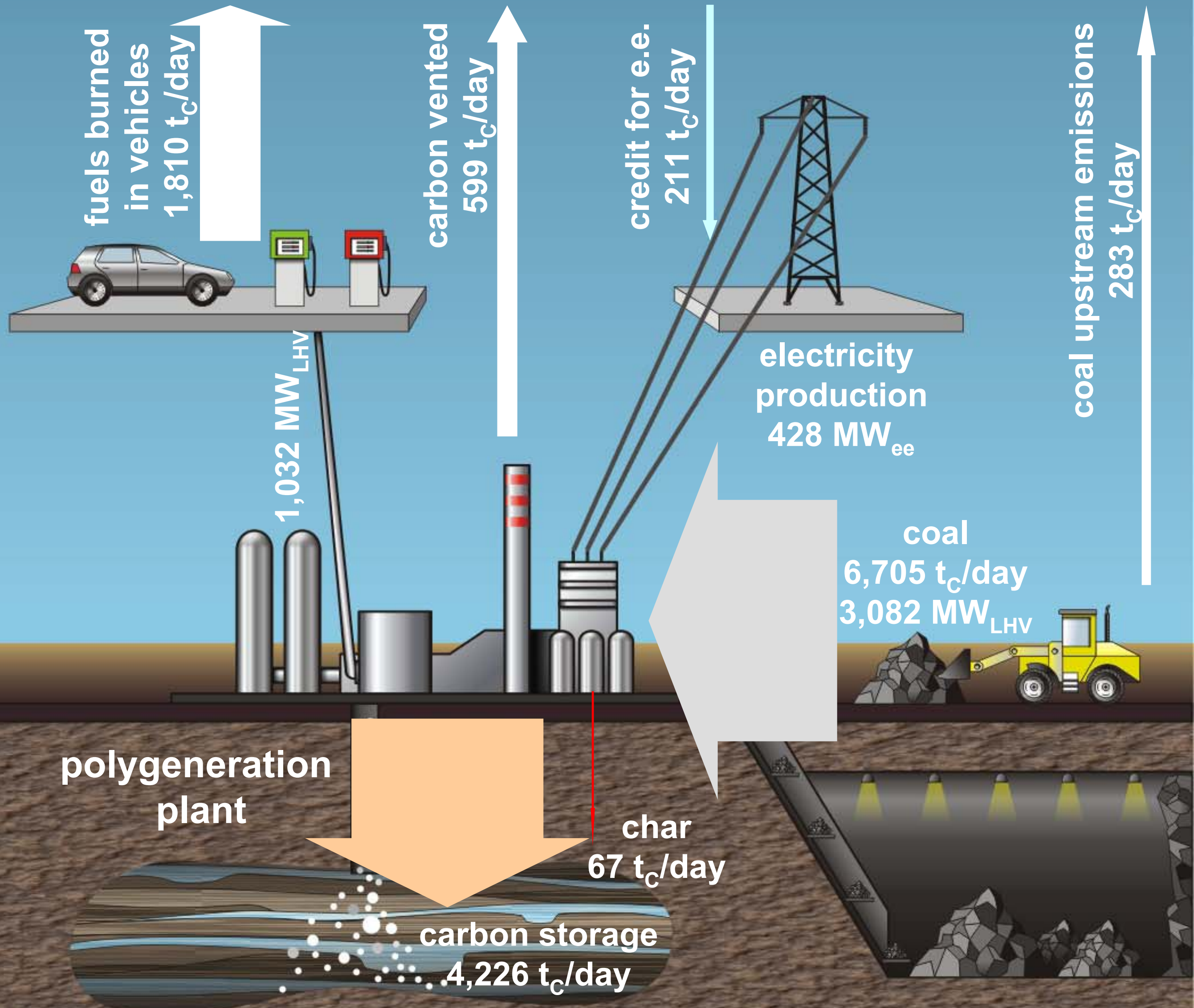
arrows’ width proportional to C fluxes

COAL TO F-T LIQUIDS + ELECTRICITY, WITH CCS

C_{equiv} balances to atmosphere for F-T liquids

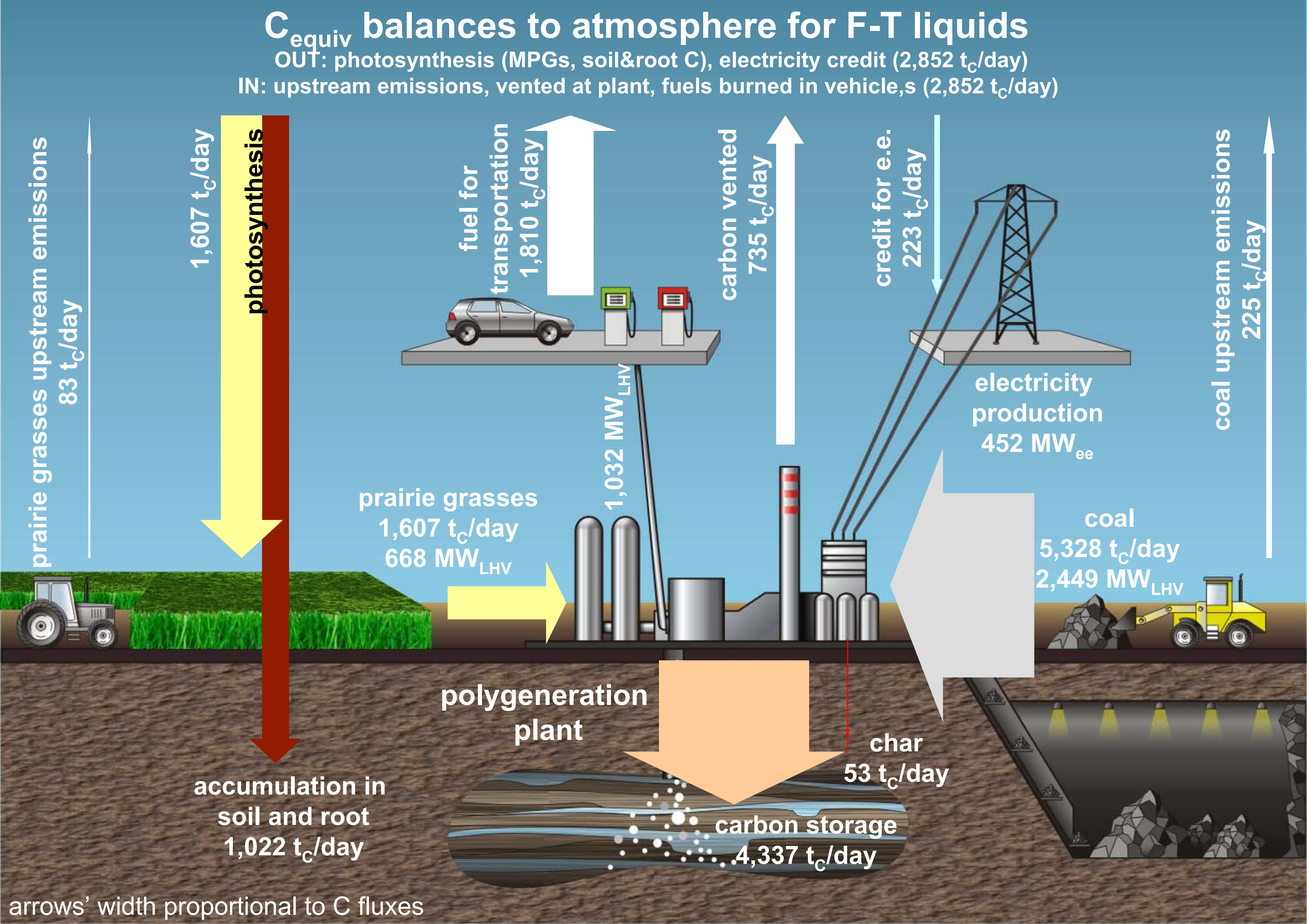
OUT: electricity credit (211 t_C/day)

IN: upstream emissions, vented at plant, fuels burned in vehicle (2,692 t_C/day)



arrows' width proportional to C fluxes

COAL + MPGs TO F-T LIQUIDS + ELECTRICITY, WITH CCS



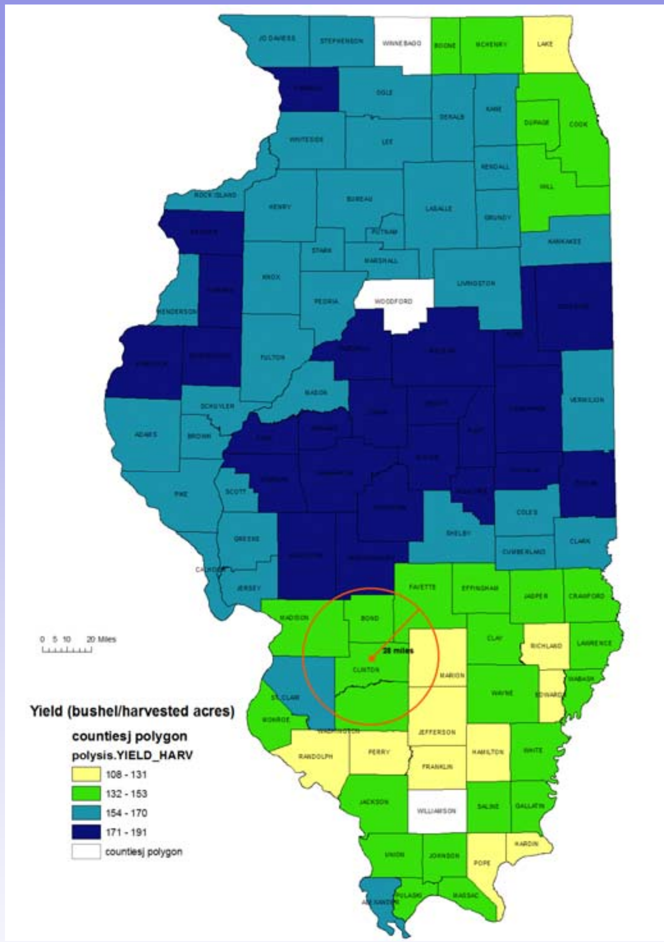
ESTIMATING VALUE OF STRATEGY TO FARMER

- Consider first coal F-T polygeneration plant with CCS
  - Site: Southern Illinois (*corn country*)
  - CO_2 storage: 7500 ft underground, Mt. Simon aquifer (*33 miles from FTL plant*)
  - Feedstock: high-S bituminous coal @ \$1.13/GJ (*LHV*)
  - GHG emissions price: \$100/tC

  ➔
  - Breakeven crude oil price = \$49/barrel
  - FTL selling price = \$1.62/gallon gasoline-equivalent
  - Electricity selling price = \$65/MWh (*generation cost for coal IGCC with CCS*)
- Next consider coal/MPG F-T polygen plant with just enough MPGs input to reduce net GHG emisison rate to zero for FTL & assume:
  - Estimated MPGs yields for lands now growing corn there
  - Same outputs/product prices as for coal-only plant with CCS

    ➔ determines "willingness" of synfuel producer to pay for MPGs = \$96/dt
- **What is income to farmer if MPGs displace corn compared to income from corn?**

SITE FOR COAL/MPGs POLYGENERATION PLANT



MPGs logistics analysis

10^6 dt/y of MPGs needed at polygen plant

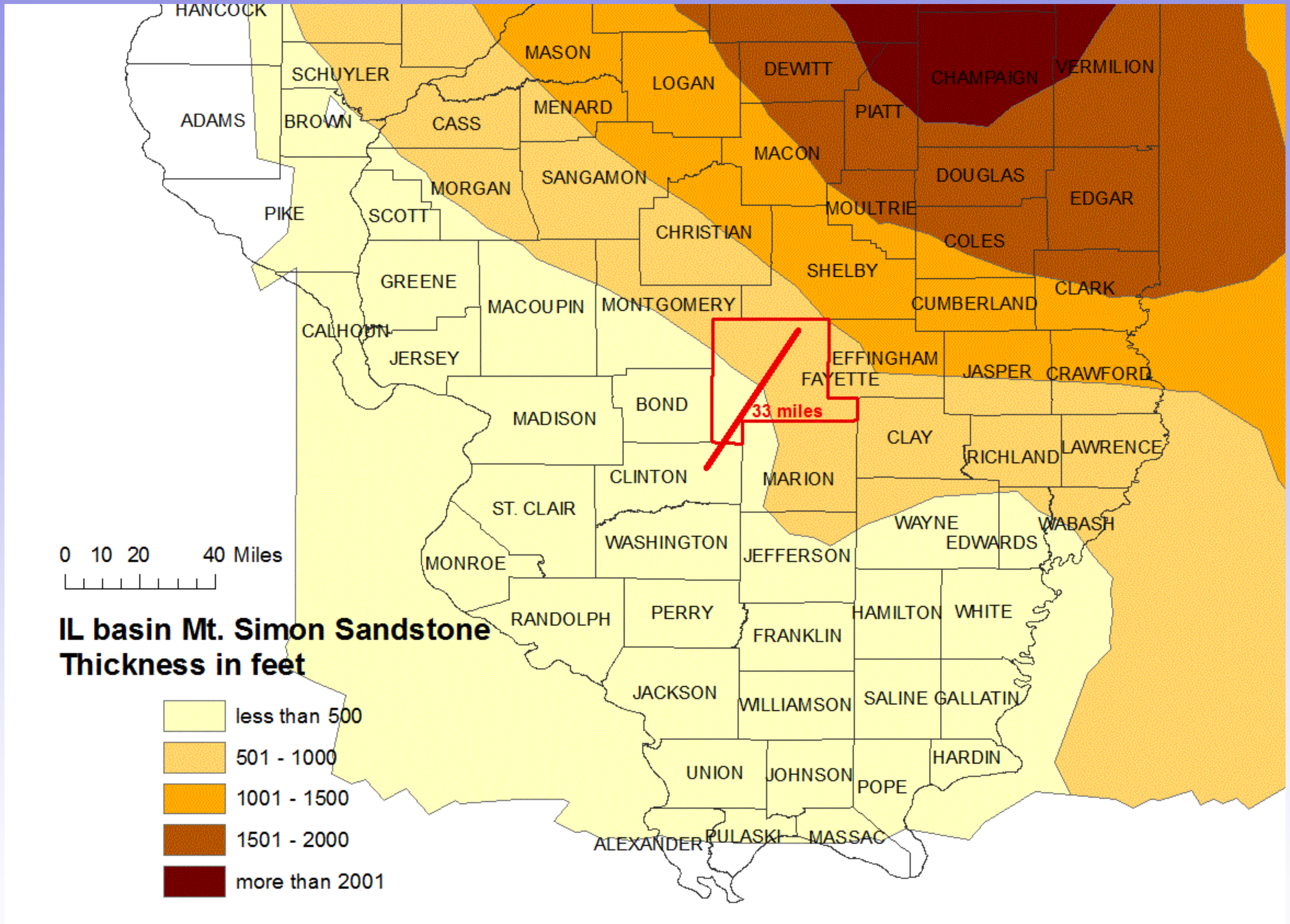
Assumed MPG yield = 10.4 dt/ha/y[a]

Assuming MPGs are grown on 15% of land around polygen plant

Ave transport distance for MPGs = 27 miles

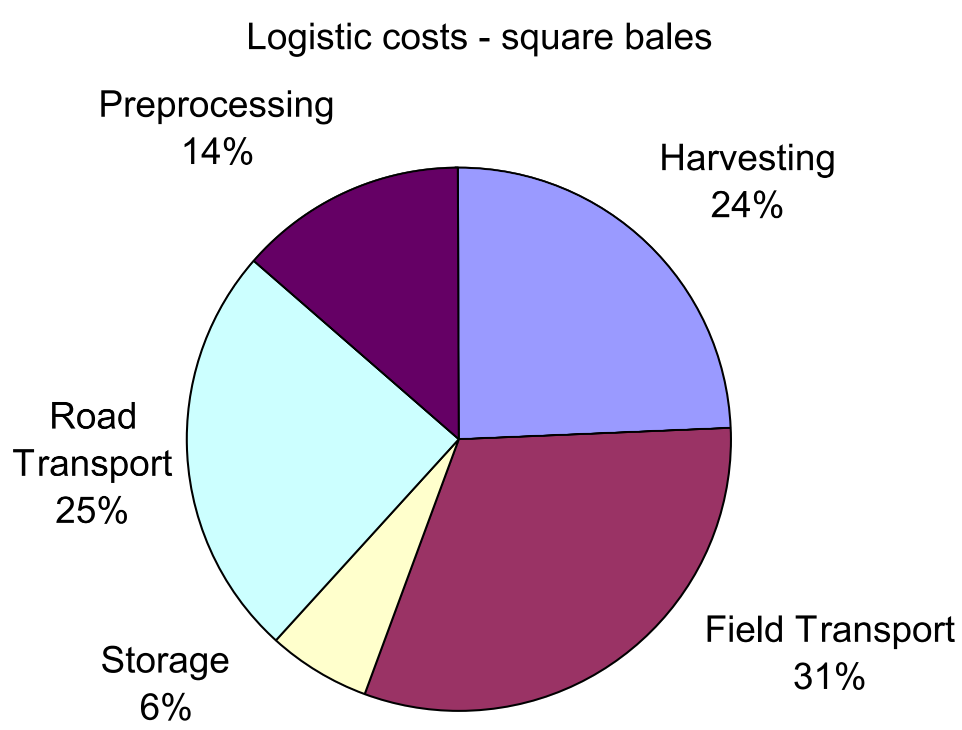
[a] Clarence Lehman, U. of Minnesota (*private communication, April 2007*), estimates that MPG yield on average cropland would be approximately 1.5 X hay yield on lower-grade local land growing hay, based on correlation of actual hays and general productivity models…here assumed yield = 1.5 X hay yield.

POSSIBLE AQUIFER STORAGE SITE



Suggested region for aquifer CO_2 storage near proposed polygeneration plant offered by Hannes Leetaru, and map of Mt Simon Sandstone features provided by Chris Korose —both of the Illinois State Geological Survey, private communication April 2007

LOGISTICS COSTS FOR MPGs



Logistics costs ($/dt) **yield 10.4 dt/ha/y**	
Harvesting	8.4
In-Field Transport	10.7
Storage (*tarping*)	2.2
Road Transport	8.4
Preprocessing (*grinding*)	4.7
Total	**34.4**

Dry matter loss with tarping is 7% (Duffy, 2003)

ECONOMICS OF SHIFTING ILLINOIS CORN TO MPGs FOR MAKING FTL WITH COAL

Assumed carbon price, $ per tonne of C	100
Breakeven oil price for coal FTL, $ per barrel	49
FTL price, $/gallon of gasoline equivalent	1.62
Assumed MPGs yield, dt/ha/y (*1.5 X local hay yield on lower-grade land*)	10.4
MPGs price, $ per dry tonne	
Willingness to pay for MPGs at FTL plant	96
Logistics costs for MPGs	-34
Income to farmer *($/tonne)*	**62**
Income to farmer (*$/ha/y*) for Bond, Clinton, Madison, and Marion counties	
For sale of grasses to FTL plant	**594**
Corn returns (*acreages, yields = 2001-2004 averages, 2007 farm prices*)	**601**

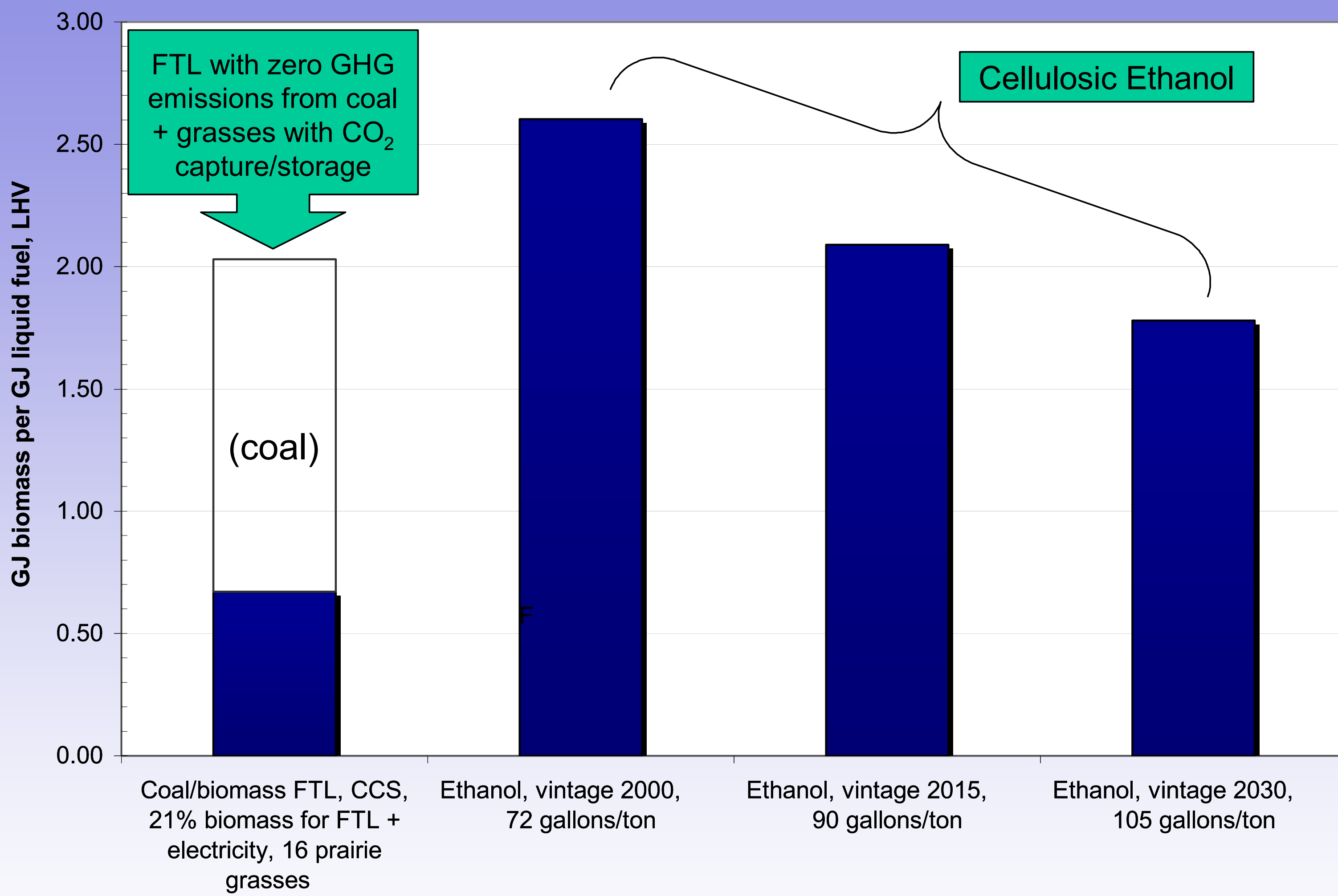
Farm data from Chad Hellwinckel & Daniel de la Ugarte, U. of Tennessee, private communication, April 2007

ECONOMICS OF SHIFTING CORN TO MPGs FOR MAKING FTL—IF SOIL/ROOT C CREDIT = 0

Assumed carbon price, $ per tonne of C	100
Breakeven oil price for coal FTL, $ per barrel	49
FTL price, $/gallon of gasoline equivalent	1.62
Assumed MPGs yield, dt/ha/y (*1.5 X local hay yield on lower-grade land*)	10.4
MPGs price, $ per dry tonne	
Willingness to pay for MPGs at FTL plant	66
Cost of harvesting, grinding, storing MPGs	-34
Income to farmer *($/tonne)*	**32**
Income to farmer (*$/ha/y*) for Bond, Clinton, Madison, and Marion counties	
For sale of grasses to FTL plant	**305**
Corn returns (*acreages, yields = 2001-2004 averages, 2007 farm prices*)	**601**

Farm data from Chad Hellwinckel & Daniel de la Ugarte, U. of Tennessee, private communication, April 2007

Biomass Required to Make 1 GJ of Liquid Fuel



Coal use (*in FTL bar*) = (total coal use for plant)

– (coal required for making same electricity in stand-alone IGCC with CCS)

The FTL option is for case in which soil/root C credit is 0.6 tC/tC in harvested MPGs

CONCLUSIONS

- If CCS becomes a major industrial activity for coal in a carbon-constrained world, it could be pursued for biomass as well as coal
- Making F-T liquids with CCS from coal + biomass makes it feasible:
  - To exploit simultaneously
    - Negative GHG emissions potential of photosynthetic CO_2 storage
    - Scale economies of coal conversion
    - Low cost of coal
  - For coal to play a significant role in providing climate-friendly synfuels
  - For biomass to play a much larger role than with conventional biofuels
- For MPGs grown on C-depleted soils the climate-change-mitigation benefits would be greatly enhanced by the buildup of root and soil C
- Zero net GHG-emitting F-T liquids derived from coal and MPGs:
  - Would be competitive for oil @ $50/barrel and C emissions valued @ $100/tC
  - Growing MPGs on C-depleted for sale into this market would be as economically attractive to the farmer as growing corn
- Without the GHG benefit of soil/root C buildup this option would be much less attractive to biomass producers